Health and Economic Impact of Wildfires: Literature Review

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Abstract

This review study synthesizes available literature in epidemiology, economics and wildfire-related studies to provide essential information for the valuation of health costs associated with wildfire events. We review three areas within these literatures: key health outcomes to be evaluated, association between wildfire smoke and health outcomes, and valuation of health effects. We find that the key health outcomes are mortality, restricted activity days (including work days lost), hospital admissions, respiratory symptoms, and self-treatment. Our review shows somewhat inconsistent results between the conventional and wildfire-related PM epidemiology studies. We summarize the recent estimates of per unit cost of mortality and morbidity and present recommendations for evaluators.

Key words: wildfire, health impact, health valuation, epidemiology studies, particulate matters

Introduction

The potential health risk from diminished air quality during wildfire events is a serious social concern. Many studies document that wildfires produce various air pollutants and often report that the ambient concentration of particulate matters (PM) increases substantially during a wildfire period. Epidemiology studies report significant morbidity and mortality impacts of PM, suggesting a potential for considerable health risks from wildfires. Evaluating the social cost associated with the health damage due to wildfire events is critical to determine the optimal wildfire management policy. Assessing this economic cost consists of multiple steps. First, the change in the air quality level due to the wildfire event must be evaluated. Second, the relationship between changes in air quality and the health impacts in wildfire-smoke affected communities must be established to estimate the total change

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in morbidity and/or mortality due to wildfires. Third, the estimated change in morbidity and/or mortality must be measured in monetary terms. Each aspect of the economic analysis requires specific procedures and data.

This review study synthesizes available literature in epidemiology, economics and wildfire-related studies to provide essential information for the valuation of health costs associated with wildfire events. We focus on three issues: the health outcomes to be evaluated, whether epidemiology studies of urban air pollution are applicable to evaluate wildfire smoke health damages, and recent findings from health valuation literature. We constrain our epidemiology literature review to the major pollutant of wildfires, PM.

Health outcome coverage

The U.S. Environmental Protection Agency (U.S.EPA) lists the wide range of potential health outcomes from PM exposures (U.S.EPA 1999).[5] While wildfires may result in wide range of health outcomes, there are limited studies that examine the distribution of health outcomes resulting from wildfire events. Anaman (2001) surveyed a community in the southeastern Asian country of Brunei affected by a large wildfire that occurred in Indonesia during 1997 and 1998 (hereafter we call this event 1997 Southeast Asian Haze). Based on 102 randomly selected households, the author finds that 2 percent of the households experienced hospitalization of a household member, and 22.5 percent experienced outpatient care of a household member due to the haze. Six percent of the sample reported some kind of self-treatment and 57 percent reported that a household member took leave of absence from school or work. To our knowledge, there has not been such survey of general population in the U.S. following a wildfire.

Table 1 summarizes previous studies that evaluated the economic cost of wildfires. All tables in this paper are available at www.fs.fed.us/rm/value/puertoricowildfire.html. None of these studies cover all health outcomes listed in the 1999 U.S.EPA report, but rather select the health outcomes based on the available information. The cost estimate of health effects due to smoke from wildfire events ranges from $0.26 million to $1,201 million[6] depending on the scale of the fire, and health outcomes considered.

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[5] Potential health impact of PM exposure listed in U.S.EPA (1999) include: mortality, bronchitis (chronic and acute), new asthma cases, cardiorespiratory-related hospital admission, emergency room visits, lower and upper respiratory illness, respiratory symptoms, minor restricted activity days, restricted activity days, work lost days, moderate or worse asthma status, neonatal mortality, changes in pulmonary function, chronic respiratory diseases, morphological changes, altered host defense mechanisms, and cancers.

[6] All monetary values in this paper are converted to 2007 US$ value using the consumer price index.

The studies summarized in *table* 1 identify that there are several key health outcomes. The first important health outcome is mortality. Rittsmaster and others (2005) estimate that a short, moderate scale forest fire in Canada contributed to 2.6 additional mortality cases at a cost of $11 million. This mortality cost accounts for more than 90 percent of total health-related costs associated with that particular forest fire. Since other economic studies listed in *table* 1 do not include the mortality cost, they may underestimate the health cost substantially.

Work days lost, restricted activity days and minor restricted activity days contribute substantially to total morbidity-related costs, and account for 36 to 74 percent of the total cost. Hospital admissions, respiratory symptoms and self-treatment are other major health costs. If every possible health outcome associated with a wildfire cannot be measured, at least mortality and these major morbidity effects should be evaluated.

Epidemiology studies: urban air pollution vs. wildfire smoke

There are a considerable number of PM-related health studies. However, most studies evaluate the health impact of persistent low to moderate levels of PM emitted from urban air pollution sources, such as fossil fuel burning (hereafter we call these PM studies conventional PM studies). Wildfires often cause short, but high levels of PM due to the vegetation burning. Whether there are different health risks from PM exposure due to urban air pollution versus wildfires is an important research question. If there is no difference, we can simply use previously estimated dose-response functions from conventional PM studies to estimate the level of health damages from wildfires.

To examine this issue, we will compare the study results from conventional PM studies and wildfire health studies in the next sections. Since conventional PM literature is substantial, we rely mainly on the U.S.EPA's extensive PM literature review (U.S.EPA 2004) as well as Pope and Dockery (2006), as references for the conventionally considered health impact of PM for mortality, hospital admissions and emergency department (ED) visits.

Conventional PM studies

Table 2 summarizes the selected study results of health effect of a short-term exposure to PM10[7] in the U.S.EPA (2004) and Pope and Dockery (2006). Conventional PM studies generally find a statistically significant impact of mortality, cardiorespiratory-related hospital admission, and asthma related ED visits from a short-time exposure to PM10, although the estimated impact is fairy small. The

[7] PM10 is the particles less than 10 micrometers in diameter.

health impact is age-specific, and also illness specific. Generally, the impact of PM10 exposure on respiratory-related illnesses is higher than on cardiovascular-related illnesses. Within respiratory-related hospital admissions, asthma and pneumonia show a higher risk than chronic obstructive pulmonary disease (COPD) from the PM exposures. The excess risk for asthma-related ED admission is also significant as PM10 levels increase.

There are limited studies that examine the relationship between restricted activity days and the PM level. Ostro and Rothschild (1989) use the National Health Interview Survey data, a continuous survey of the health status of the U.S. population collected by the National Center for Health Statistics. They find that a 1ug/m3 increase of fine particulate matter results in a 1.58 percent increase in restricted activity days (RRAD),[8] and a 0.82 percent increase in minor restricted activity days (MRAD)[9] among an 18 to 65 year old sample.

Wildfire health impact studies

Tables 3, 4 and 5 present the epidemiology studies that examine the association between wildfire events and mortality, hospital admission and ED visits, respectively. We only include studies that examine the statistical significance of the results.[10] In the tables, studies are listed by the estimation method and the order of the maximum PM level recorded during the wildfire event (from the lowest to the highest). While conventional PM studies reviewed in this paper use the daily time-series analysis method, wildfire health impact studies use the time-series analysis as well as the historical control method. The historical control method compares the total or average level of health effect during the event period to a similar duration of the control periods.

While conventional PM studies find a statistically significant positive mortality and morbidity impact from a short-time exposure to PM, not all wildfire health impact studies find statistically significant health impacts. Among mortality impact studies (*table* 3), only two of six studies find a significant mortality increase of the mortality level during a wildfire event.[11] As for hospital admissions studies (*table* 4),

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[8] RRAD is defined as "any day on which a respondent was forced to alter his or her normal activity and an acute respiratory condition was reported. It includes days of work lost or bed disability as well as more minor restriction" (p 239)

[9] MRAD is defined as "a restricted activity day that does not result in either work loss or bed disability and therefore involves more minor conditions and reductions in activity." (p 239).

[10] Naeher and others (2007) also provide comprehensive review of epidemiology studies of vegetation fires as well as controlled laboratory studies of wood smoke, health effect of residential wood burning, toxicology, chemical and physical nature of wood smoke. Our study expands their epidemiology literature review of mortality, hospital admission and ED visits by adding studies that are not included as well as by adding the analytical structure.

[11] If author(s) uses different analysis methods, multiple study locations or different samples (except different age group categories) within one study, we count each estimation result as if they come from separate studies.

while all studies that considered respiratory-related effect find a significant impact, only two out of six studies that considered asthma-related effects find a significant increase attributable to a wildfire event. One of the two studies that considered cardiovascular effects finds a significant increase of hospital admissions during wildfire events. Among ED visit studies (*table* 5), six out of the fourteen studies that considered asthma-related effects, nine out of the thirteen studies that considered respiratory related effects, and none of the three studies that considered cardiovascular effects find a significant increase in ED visits during wildfire events.

Since many wildfire healths impact studies use different units to present the health impact of wildfire smoke exposures, their results are not generally comparable with the PM health impacts reported in the U.S.EPA (2004). We will briefly discuss the studies that show comparable results.

Sastry (2002) studies the mortality impact of the 1997 Southeast Asian Haze on the Malaysian population using the daily time series model. The author finds a significantly positive association between PM and mortality levels among the elderly. The magnitude of the mortality effect is compatible with conventional PM studies. However, the mortality impact is found to be significant only after very high pollution days (daily PM = 200ug/m3). Including days with lower levels of PM substantially weaken the results. This is in contrast to the fact that conventional PM studies find a significant mortality impact even at lower levels of PM.

In general, we have very limited evidence of mortality impacts associated with wildfire events. Kunji and others (2002) also report a weaker mortality impact from the wildfire smoke than the urban air pollution. Kunji and others observe 527 deaths during the 1997 Southeast Asian Haze episode in haze-affected areas in Indonesia while the conventional PM studies employed in the World Health Organization guideline predicted 15,000 deaths.

Johnston and others (2002) and Chen and others (2006) study the effect of prolonged bushfire events on ED visits and hospital admissions in Australia, respectively. Both studies find a higher health impact during the bush fire periods as compared to results from conventional PM studies. However, Chen and others (2006) also find a relatively high PM risk level during a non-bushfire period, which indicates the potentially higher PM health impact in Australia as compared to the U.S. Cançado and others (2006) study the effect of a sugar cane burning event on hospital admissions and find a significant impact among children and the elderly. Chen and others (2006) and Cançado and others (2006) also find a higher health risk during fire periods than non-fire periods.

Hospital admission and ED visit based studies provide mixed evidence of the health risk from wildfire smoke. Several studies do not find a significant health impact, while some studies suggest a more hazardous nature of wildfire smoke.

Lastly, Sastry (2002) and Johnston and others (2002) find a non-linear health impact of wildfire oriented PM exposures, where significant health impacts are found only when PM levels exceed certain levels.

Difference between conventional and wildfire PM studies

Vedal and Dutton (2006) and several researchers discuss the potential reasons for inconsistencies between conventional PM studies and wildfire health impact studies. Following five explanations may be of particular importance: 1) choice of statistical models, 2) chemical composition, 3) non-linearity of PM dose-response function, 4) averting behavior, and 5) perception about health risk. We briefly discuss each explanation.

The first explanation for the inconsistent results between conventional PM studies and wildfire studies is the use of different statistical methods. The conventional PM studies often use daily time-series models with a long observation period. A large sample size likely enables researchers to detect a small health impact from a short-term PM exposure.[12] The historical control method, often employed in wildfire health impact studies, compares a total or average health outcome level between the study and control periods. When health outcomes show a small variation over time, it would be difficult to detect a small health impact from this method (Vedal and Dutton 2006). In fact, none of the historical control studies that evaluate the impact of mortality and asthma-related hospital admission finds significant results, potentially because of the lack of statistical power.

Even with time series models, conducting a wildfire related health impact study is challenging. Wildfire events are generally short, and it is difficult to study a separate health impact of wildfire events using the daily time-series model due to the small number of observations of interest. The studies that find a significant increase in mortality and hospital admissions during wildfire periods tend to use long observation periods (Sastry uses 13 to 33, and Chen and others use 452 smoke affected days).

The second explanation is that there exists a different chemical composition between urban air pollution and wildfire smoke. Vedal and Dutton (2006) argue that the fossil fuel combustion usually contains toxic particles such as metal, and may be more hazardous than vegetation burning. However, Mar and others (2000) did not find significantly different health impacts of PM from fossil fuel and vegetation burning. The difference they find is that the burning vegetation shows a longer

[12] See also Vedal and Dutton (2006) for the discussion of potential bias in conventional time series PM models. Naeher and others (2006) also provide a discussion about the limitation of several studies with short-observation and few reference periods.

lagged mortality effect.[13]

The third issue is the potential non-linearity of the PM dose-response function. Wildfires cause a relatively short, but high level of PM, while urban air pollution causes persistent low to moderate levels of PM. The U.S.EPA (2004) concludes that the PM dose-response function is linear at low to moderate levels. However, the functional form is still uncertain at high PM exposure levels. As several wildfire health impact studies indicate, it is possible that we have a non-linear PM dose-response function at high levels of PM exposure.[14] If this is the case, applying the dose-response function obtained from low-to-moderate level PM exposures to estimate the health impact of high levels of PM exposures would substantially bias the results.

The fourth issue is the potential different averting behaviors among residents in smoke affected areas during wildfire events (Vedal and Dutton 2006, Kunji and others 2002). Studies find individuals, particularly those who are sensitive to air pollution, take averting measures when the air pollution level is high (Bresnahan and others 1997, Künzli and others 2007). Since large wildfire events are highly publicized by mass media and/or local officials, and smoke is highly visible, individuals may take more measures to avoid air pollution exposures than usual. If individuals take more averting actions during wildfire events than non-wildfire events, the actual PM exposure level is lower, and results in less health impacts at a given level of outdoor PM.[15]

The fifth reason is a potentially different perception of health risk towards urban air pollution versus wildfire events. Lipsett and others (1994) find that about four times as many people without physical evidence of illness visited an ED during a large urban fire event than usual. This finding indicates that the perception of seriousness of illness dramatically increases during a large fire event. This factor will not affect the level of mortality and would not likely affect the level of hospital admissions. However, other relatively minor health outcomes, such as ED visits and perceived symptoms of cardiorespiratory illness, may be affected substantially by the overestimation of health risk from wildfires.

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[13] A related issue is the different sizes of particles between urban air pollution and wildfire smoke. Wildfire smoke mainly contains fine particles which are less than 2.5 micrometers in diameter (Ward 1999). Some studies suggest that fine particles are more hazardous than course particles (2.5-10 micrometers in diameter) (U.S.EPA 2004). If this is the case and urban air pollution contains larger proportion of coase particles than wildfire smoke, wildfire smoke would be more hazardous than urban air pollution.

[14] See Martin and others (2007) how they assume the dose-response relationship at a high PM levels.

[15] See also Vedal and Dutton (2006) and Kunji and others (2002) for the discussion of the effectiveness of averting behaviors during wildfire events.

Future research

There is still significant uncertainty about the health risk of wildfire smoke. Many mortality studies and several hospital admission and ED visit studies find no significant impact on health outcomes, even though conventional PM studies predict significant impacts. When significant results are found in wildfire health impact studies, results are somewhat inconsistent with results from conventional PM studies.

The level of PM health impact would be affected by not only the PM levels, but also by the characteristics of the affected population and study design. The strict comparison between results from previous conventional PM studies and wildfire health impact studies is difficult due to the different population samples and study designs. Future studies should evaluate the health impact of wildfire smoke and urban air pollutions with the same study design using the same samples. Such studies have been done by Chen and others (2006) and Cançado and others (2006) using Australian and Brazilian samples, but no such study has been conducted with a U.S. sample. Studying the health impact of large prolonged (or repeated) wildfires near urban areas could be a key to obtaining meaningful results, since the health outcome variation may not be large enough during the short and small scale wildfires.

Using the daily time series model is a preferred approach to evaluate the wildfire health impact. This model is more likely able to detect significant small changes of health outcomes during the wildfire period than the historical control method. The time series model can test different hypotheses about which of the five factors addressed above play critical roles in the observed difference in the health impact from wildfire smoke and urban air pollution. Another benefit of using time-series analysis is that the dose-response function obtained from this method is easily used to evaluate the health impact of different wildfire events. However, this method requires a minimum of "wildfire day" observations, which may make the application difficult.

Another potentially useful study would be a meta-regression analysis using various wildfire health impact studies. The estimated total wildfire health impact would be the dependent variable, and outdoor PM and other pollutants levels, affected population characteristics, and type of fuels, would be independent variables. This approach would enable researchers to estimate the future wildfire health impact after adjusting to the different affected population characteristics and fuel types. To obtain a good meta-regression model, we need to accumulate more wildfire health impact studies in North America with consistent presentation of health impact results.

Surveying communities about experience with cardiorespiratory symptoms and averting behaviors during wildfire events, as well as risk perceptions associated with wildfires, will help us estimate the potential health impact in terms of cardiorespiratory symptoms and restricted activity days associated and improve our understanding of the potential disparity of health impacts due to wildfire smoke and urban air pollution.

Economic evaluation

The health damage from wildfire events incurs direct and indirect costs to society. Freeman (2003) divides the health damage associated cost into four categories: 1. medical cost, 2. labor loss, 3. averting cost and 4. utility loss (discomfort, suffering) associated with health damage. From the economic efficiency standpoint, the total cost associated with health damage should be estimated by the individual's willingness to pay (WTP) to avoid such health damages. The U.S.EPA (1999) uses the health valuation literature to list the plausible value of per unit costs of health outcomes, as in *table* 6. In this section, we review more recent health valuation literature and discuss whether the U.S.EPA list should be modified.

Mortality valuation

The monetary value of preventing mortality is measured as the value of a statistical life (VSL). The VSL is society's aggregated willingness to pay to save one anonymous person's life. Viscusi (1992) provides a comprehensive review of VSL literature. The U.S.EPA (1999) uses the average value of Viscusi's selected 26 VSL estimates, $7.6 million, to evaluate the mortality benefit of air pollution control. Out of 26 VSL estimates, 21 estimates are based on the labor market data, and 5 estimates are based on the survey studies. Later, the U.S.EPA updated the VSL to $6.8 million based only on the labor market studies (U.S.EPA 2005).

Recent studies find that labor market studies used in the U.S.EPA (1999, 2005) analysis likely overestimate the actual VSL due to incorrect model specifications. Kniesner and others (2006) and Kochi (2006) correct the bias and report the revised VSL of $5.4 million and $2 million, respectively. Other recent studies find that the VSL is not age dependent but health status dependent among the U.S. population (Alberini and others 2004). The mean VSL estimated in Alberini and others (2004) is between $0.87 and $5.99 million for the U.S. population.

In conclusion, these recent studies suggest that the plausible range of the VSL would be $1 million to $6 million with an adjustment for the part of the population with existing health conditions.

Morbidity valuation

The morbidity valuation is more complicated than the mortality valuation due to the various potential health outcomes with different levels of severity and duration. The detailed review of morbidity valuation methodologies is available in Tolley and others (1994) and Dickie and Gerking (2002). The U.S.EPA (1999) lists per unit cost of morbidity outcomes estimated based on the Cost of Illness (COI) method or the contingent valuation (CV) method. The COI method only estimates the direct expenses associated with illness, such as the medical cost and lost wages to treat the illness. The CV method measures individual's willingness to pay (WTP) to prevent a hypothetical occurrence of illness.

The U.S.EPA (1999) uses $10,000 to $15,000 as per cadiorespiratory-related hospitalization cost based on the conventional COI that includes direct medical cost and labor loss during the hospitalization. A recent study by Chestnut and others (2006) finds that the time lost during the recovery period at home is about five times longer than the time lost from work during hospitalization among cardiorespiratory patients. Adding COI values incurred during recovery period, lost household production, and cost associated with caregivers increases the conventional COI estimate by 9 to 32 percent.[16]

The estimated COI needs to be converted to the WTP measure. A widely used WTP/COI ratio is 2 to 3.[17] In a hospital admission event, most of the medical expenses are paid by the insurance company, and some patients have sick leave benefits. The conversion to WTP should be based on the out-of-pocket expenses associated with hospitalization, not based on the expenses paid by a third-party. Thus, the final economics measure of hospitalization should be the COI accounting for the third party payment plus the individual WTP as presented in Chestnut and others (2006).

These issues also apply to the economic cost estimation of ED visits. The U.S.EPA (1999) uses the conventional COI measure. This measure excludes expenses associated with caregivers, cost incurred during the recovery period, and utility reduction. Since no study has evaluated this part of the cost of ED visits, the results from Chestnut and others (2006) may be utilized to obtain the full COI values. In addition, COI measures should be converted to the WTP measure.

Dickie and Gerking (2002) list selected studies that estimate WTP to prevent acute cardiorespiratory symptoms using the CV method. *Table* 7 modifies Dickie and Gerking's list by including slightly different set of studies and estimates. As noted by Dickie and Gerking (2002), WTP values used by the U.S.EPA (1999) are generally lower than recently estimated values. For example, the U.S.EPA uses $75 per acute bronchitis case. Dickie and Messman (2001) estimate the WTP to prevent a 6-day long acute bronchitis case[18] as $201 (median value) and Navrud (2001)[19] estimates

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[16] The COI per hospitalization also depends on the age of the patient and category of illness. Elderly (over 65) have lower COI than younger individuals due to the smaller value of lost work days.

[17] Hrudey and others (2004) suggest to use the WTP/COI ratio of 2 to 3 to estimate the benefit of air pollution control in Canada. Hon (1999) and Ruitenbeek (1999) use the WTP/COI ratio of 2.

that the WTP to reduce 14-day acute bronchitis symptoms as $82 (mean value). The mean WTP to reduce one asthma attack episode used by the U.S.EPA is $50. Navrud (2001) reports the mean WTP to reduce one asthma attack episode as $236.

The U.S.EPA uses $28 as the WTP to avoid acute respiratory symptoms per day, while Dickie and Messman (2004) estimate it as $90. The U.S.EPA uses $8 as the WTP to avoid one day of shortness of breath, chest tightness or wheezing. Dickie and Messman (2004) report the mean WTP to avoid 6-day shortness of breath and chest tightness as $130 ($22 per day) and $101 ($16.8 per day), respectively. Navrud (2001) estimates $39 (mean value) and $15 (median value) to avoid one day of shortness of breath.

It is not clear why older studies report generally lower WTP estimates than more recent studies. However, recent studies incorporate methodological advances of morbidity evaluation, and should be given more weight to determine the morbidity value to evaluate the health-related policy. Thus the U.S.EPA's morbidity value list should be updated to reflect these new findings. Maybe the best way to incorporate results from different studies is to estimate a meta-regression model using existing morbidity valuation studies. The meta-regression model would enable researchers to obtain the WTP for each morbidity outcome for different severity and durations, after accounting for the different study design among existing valuation studies (Van Houtven and others 2006).

Finally, Dickie and Messman (2002) and Navrud (2001) consistently find that the WTP to prevent children's morbidity is substantially higher than adult's morbidity. This indicates the importance of valuing the adult and children morbidity impacts separately.

Recommendation

In this paper, we review three important issues in the economic analysis of the effect of wildfires on health: key health outcomes, association between wildfire smoke and health outcomes, and valuation of health effects. We find that the key health outcomes are: mortality, restricted activity days (including work days lost), hospital admissions, respiratory symptoms and self-treatment. Our review of the conventional and wildfire-related PM epidemiology studies poses an important question of whether or not conventional PM epidemiology results can be used to evaluate the health impact from wildfire events.

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[18] Authors find that the average acute bronchitis symptom lasts an average of 7-days among the sample.
[19] Navrud (2001) uses samples in Norway, and authors caution that the estimation results of this study may underestimate the WTP for the U.S. population due to different health care systems.

We do not recommend applying conventional PM epidemiology results to evaluate the mortality impact of wildfire events at this point. Although the conventional PM epidemiology studies generally show statistically significant mortality increases associated with short-term PM exposures, the majority of wildfire-PM studies do not find similar results. Simply using the conventional PM epidemiology results may substantially overestimate the mortality health cost associated with a wildfire event.

Since mortality is associated with a very large social cost, the estimation of the mortality impact due to wildfire events requires extreme caution. If the scale of the wildfire is relatively small and short, evaluators may want to assume that there is no mortality impact from the wildfire smoke while noting that there is a potential underestimation of the cost by excluding the mortality impact, or conduct an original epidemiology study. We recommend using the VSL estimate of $1 million to $6 million to evaluate the social cost of mortality, if there is any.

To estimate the changes of key morbidity outcomes from wildfire events, evaluators may want to use the results from conventional PM epidemiology studies for now, or conduct original epidemiology studies. We do not have studies that evaluate the impact of wildfire on restricted activity days in the U.S. We have some hospital admission studies and a few cardiorespiratory symptoms studies (not discussed in this paper) related to the wildfire events. However, it is difficult to derive the general association between a wildfire event and these morbidity outcomes due to the limited study design of previous findings. It is important to remember that the health impact of urban air pollution and wildfire events may be different, and the morbidity impact analysis based on conventional PM studies are still subject to this uncertainty.

We recommend using per unit cost of hospital admission and cardiorespiratory symptoms that reflect the recent findings with an emphasis on U.S. studies. Hospital admission should be based on the total medical expenses and labor loss during the hospital stay and recovery period. To convert COI values to WTP values, evaluators may want to use 2 to 3 WTP/COI ratios. Evaluators may want to use per unit values of respiratory symptoms estimated in Dickie and Messman (2004) when available. This study estimates comprehensive per unit values of respiratory symptoms with an improved health valuation method using a relatively large U.S. sample. Evaluators may also want to conduct a meta-regression analysis based on previous morbidity studies to determine the appropriate value for each severity and duration of symptoms after controlling for differences in the study design. Since the health impact and health costs are likely to be different between children and adults, evaluators should conduct the health impact study and valuation study separately for children and adults.

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Table 1 Previous economic analysis of wildfire-smoke induced health damage

	Fire	Health outcomes studied	Source of dose-response function [estimated case of health outcome due to wildfire]	Source of monetary value	Estimated economic cost (central estimate unless specified, 2007 $US value)
Cardoso de Mendonça et al.	Amazon	In-patient treatment (respiratory)	Original [annual average 9,346]	Seroa da Motta et al. 2000a,b: European estimate of WTP adjusted for Brazil condition)	Annual average =$9.4 million
				Medical expenditure (COI)	$2.1 million
Martin et al. (2007)	Hypothetical prescribed fire in Kaibab National Forest	Hospital admission (respiratory & cardiac)	Burnett et al. 1997 [3]	USEPA (1999) (COI)	$0.07 million
		Lower respiratory symptoms (Children)	Schwartz et al. 1994 [7]	USEPA (1999) (WTP for adult)*2	$0.03 million (including both children's health effect)
	Affected city: Flagstaff	Acute Bronchitis (Children)	Dockery et al. 1996 [138]	USEPA (1999)(WTP for adult)*2	
	Worst case scenario: Total 1,935 ug/m3 PM2.5 increase	Work loss days (WLD)	Ostro 1987 [175]	Average wage of Flagstaff area (COI)	$0.15 million (including WLD, RAD, MRAD)
		Restricted activity days (RAD)	Ostro 1987 [478]	Average wage of Flagstaff area (COI)	
		Minor restricted activity days (MRAD)	Ostro and Rothschild, 1989 [577]	USEPA (1999)	
		Total			$0.26 million
*Monetary value for each morbidity category used in Martin et al. comes from USEPA (1999) except for RAD and MRAD. Detailed value listed in USEPA (1999) is shown in table 6 in this paper. All epidemiology studies applied in Martin et al. examine the health effect from a small change of PM. A large change of PM is assumed to cause 1/3 of expected marginal mortality based on Pope et al. (1992) study as compared to a small change of PM. Thus authors divide estimated health outcome by 3.					
Rittmaster et al. (2006)	2001 Chisholm fire in Canada	Mortality	Pope et al. 1995; Schwarts et al. 1996 [2.6]	Air Quality Valuation Model (AQVM) 3.0	$10.9 million
	7-days fire 2-days smoke	Hospital admission (respiratory)	Burnett et al. 1995 [0.56]	Canadian Institute for Health Information (CIHI) 1994	$3,601

Peak PM2.5: 55ug/m3 daily average, 261ug/m3 hourly average	Hospital admission (cardiac)	Burnett et al. 1995 [0.47]	(COI) Canadian Institute for Health Information (CIHI) 1994 (COI)	$3,880
	Emergency room visits	Stieb et al. 1995 [2.60]	Rowe et al. 1986 (COI)	$1,451
In the analysis, assume exposure level 55ug/m3 and 35ug/m3 24 hour average in Edmonton (1 million people) and Red Deer, respectively.	Asthma symptom days	Whitemore and Korn 1980; Ostro et al. 1991 [722]	Row and Chestnut 1986 (WTP)	$32,270
	Restricted activity days	Ostro 1987; Ostro and Rothschild 1989 [78,65]	Loehman et al. 1979 (WTP, COI)	$557,503
	Acute respiratory symptom events	Krupnick et al. 1990 [1,197]	Loehman et al. 1979 (WTP)	$169,789
	Childhood bronchitis	Dockery et al. 1996 [61]	Krupnick and Cropper 1989 (COI)	$18,132
	TOTAL			**$11.7 million**

*Rittmaster et al. use the Air Quality Valuation Model (AQVM) to assess the impact of PM2.5 on health outcomes and its monetary value. Rittmaster et al. present the source of AQVM in Table 1 and 2 in their paper, and above table is created based on Rittmaster et al.'s tables. Rittmaster et al.'s tables are extracted from Chestnut et al. (1999). Detailed description of AQVM is also available in Adamowicz et al. (2004). Rittmaster et al. do not provide exact numbers of estimated health outcome. We estimated them based on the total economic cost and per unit economic cost provided by authors and description of AQVM (Adamowicz et al., 2004). Canadian dollar is converted to US dollar using 1996 average exchange rate ($CAN:$US=1:0.73)

Shahwahid and Othman (1999)	1997 Asian Haze in Malaysia Smoke period: August-November 1997. Air Pollution Index reached dangerous level. Declared state of emergency for 10 days	Hospitalization	Original [379]	Medical data in Malaysia (COI)	$0.6 million
		Outpatient	Original [141,112]	Medical data in Malaysia (COI)	$1.8 million
		Self-treatment	Assume outpatient:self-treatment=1: 0.5~1 based on interview with doctors [59,593]	Medical data in Malaysia (COI)	$0.2 million
		Work days lost	Original [21,501]		$0.3 million
		Reduced activity days	Original [141,068]		$1.9 million
		Total (COI)			**$4.9 million**
Hon (1999)	1997 Asian Haze in Singapore 14days unhealthy 24 hour average air quality level	Hospitalization	Original [445]	Medical data in Singapore (COI)	$0.1-$0.5 million
		Outpatient (less severe)	Original [17,305]	Medical data in Singapore (COI)	$0.6-1.6 million (including all outpatient/self-treatment)
		Outpatient (severe)	Original [8,909]	Medical data in Singapore (COI)	
		Self-treatment (less severe symptoms)	Assume outpatient: self-treated=3:2	Medical data in Singapore (COI)	
		Work days lost	Original [34,867]		$1.9-6.5 million
		Total (COI)			**$2.7-$8.7 million**
		Adjusted total (WTP)	Assume WTP:COI=2:1		**$5.5-$17.4 million**
Ruitenbeek (1999)	1997 Asian Haze in Indonesia PM10 in Jambi recorded 1,864ug/m3 (Kunji et al.,	Hospitalization	Shahwahid and Othman 1999 [267,000]	Indonesia data	$385 million (including all medical cost)
		Outpatient	Shahwahid and Othman 1999 [623,000]	Indonesia data	
		Self-treatment	Shahwahid and Othman 1999 [9,780,000]	Indonesia data	
		Work days lost	Shahwahid and Othman 1999 [27,900,000]	Indonesia data	$217 million

2002)	**Total (COI)**		**$600 million**
	Adjusted total (WTP)	Assume WTP:COI=2:1	**$1,201 million**

Table 2 Summary of U.S.EPA (2004) review of PM health impacts[a]

Health outcomes	10ug/m3[b] increase of daily PM10
Mortality	0.3-0.6%
Respiratory	0.59-2.1%
Cardiovascular	0.17-0.89%,
Hospital admission	
Respiratory	0.9%-3.7%
Cardiovascular (>64 years old)	0.5% and 1.7%
Cardiovascular (<65 years old)	0.3%-1.1%
Emergency department visit	
Asthma	2.4%-3.7%

a: The variation of risk estimation of PM comes from several sources, such as model specifications in terms of defining weather variables, season and temporal trend, confounding effect from co-pollutants, geographic heterogeneity, or chemical components.

b: All relative risk is converted to 10ug/m3 increment for consistency. For example, converting relative risk of 1.02 for 50ug/m3 increase of PM10 to relative risk of 10ug/m3 is conducted with the following equation: EXP[10/50*ln(1.02)]=1.0039 (Johnston et al. 2002).

Table 3. Wildfire-induced mortality impact summary (ordered by maximum PM10 level)

By historical control method

Study	Location	Name and studied period of wildfire	Max PM10 average level (ug/m3)	Effect on mortality
Emmanuel (2000)	Singapore	1997 Asian Haze Sep-Oct, 1997	100 (monthly)	No change
Phonboon et al.(1999)	Hatyai, Thailand	1997 Asian Haze Sep-Oct, 1997	218 (daily)	No change (positive, but not significant)

By time-series method

Study	Location	Name and studied period of wildfire	Max PM10 level (ug/m3)	Effect on mortality
Cardoso de Mendonça et al. (2006)	Amazon, Brazil	Burning of Amazon forest between 1996-1999	PM level not available. Substitute with acres of area burned.	No change
Vedal and Dutton (2006)	Colorado, US	Hayman fire 06/09 and 6/18, 2002	91 (daily) 372 (hourly)	No change
Sastry (2002)	Kuala Lumpur, Malaysia	1997 Asian Haze Sep-Oct, 1997	423 (daily) low visible days=14	Increase of PM by 100ug/m3 is associated with relative risk of total mortality 1.07 High risk: 65-74 age groups.
Sastry (2002)	Kuching, Malaysia	1997 Asian Haze Sep-Oct, 1997	Low visible days=33	Cardiorespiratory related mortality: Significant only for age>75

Table 4. Wildfire-induced morbidity impact (hospital admission) summary (ordered by maximum PM10 level)

By historical control method

Study	Location	Name and studied date of wildfire	Max PM10 level (ug/m3)	Patient type	Effect on Asthma	Effect on Respiratory symptoms*	Effect on Cardiovascular
Phonboon et al. (1999)	Thailand (region-wide)	1997 Asian Haze Sep-Oct 1997	218 (daily) 69 (monthly)	All	No change	7% increase (net)	No change
	Thailand (Hatyai)	1997 Asian Haze Sep-Oct 1997	218 (daily) 69 (monthly)	All	No change	49% increase (net, bronchitis/COPD)	NA
Duclos et al (1990)	CA, USA	Large Fire, Aug 30th-Sep 15th, 1987	237 (daily)	All	No change	NA	NA
Emmanuel (2000)	Singapore	1997 Asian Haze Sep-Oct 1997	100 (monthly)	All	No change	NA	NA

By time-series method

Study	Location	Name and studied date of wildfire	Max PM10 level (ug/m3)	Patient type	Effect on Asthma	Effect on Respiratory symptoms*	Effect on Cardiovascular
Chen et al. (2006)	Brisbane, Australia	Long-term bushfires between 1 July 1997-31 December 2000 (452 bushfire days)	60 (daily)	All	NA	Increased PM10 from low (<15ug/m3) to medium (15-20 ug/m3), or to high (>20ug/m3) is associated with 9% and 19% increase of admission, respectively	NA
Phonboon et al. (1999)	Thailand (region-wide)	1997 Asian Haze Sep-Oct 1997	218 (daily) 69 (monthly)	All	1ug/m3 increase of monthly average PM10 is associated with 13 excess admission per month	1ug/m3 increase of PM10 is associated with 85 excess admission	NA
Cardoso de Mendonca et al.(2004)	Brazil, Amazon	Burning of Amazon forest between 1996-1999	500 (used total burned area in analysis)	All	NA	1 unit of increased burned area is associated with 0.2961 case of hospitalization	NA
Shahwahid and Othman (1999)	Malaysia	1997 Asian Haze, Aug-Oct 1997	Air Pollution Index=831 (extremely high)	All	NA	1 unit of increased API measure is associated with 0.000055 case per 10,000 people**	NA
Mott et al. (2005)	Kuching, Malaysia	1997 Asian Haze, Sep-Oct 1997	852 (daily)	0-18 years old	No change	No change	No change
				19-39 years old	Increased	Increased	Increased
				40-64 years old	Increased	Increased	No change
				65+ years old	No change	No change	No change
				All	Increased	Increased	No change

*: include general respiratory symptom, upper respiratory infection, or obstructive respiratory disease
**: The original classification of disease is “cardiorespiratory illness”.
(P): proportion of the number of patient
(T): Total number of patient
NA: Estimates not available.

Table 5. Wildfire-induced morbidity impact (Emergency Department (ED) visit) summary (ordered by maximum PM10 level)

By historical control method

Study	Location	Name and studied date of wildfire	Max PM10 level	Patient type	Effect on Asthma	Effect on Respiratory system*	Effect on Cardiovascular system
Churches and Corbett (1991)	Sydney, Australia	Burning of firebreaks, May 1991.	Nephelometry reading=7.5 (hourly)	ED	No change	NA	NA
Cooper et al. (1994)	Sydney, Australia	Bushfire, Jan 1994	Nephelometry reading=2.3 (daily)	ED	No change	NA	NA
Smith et al. (1996)	Sydney, Australia	Bushfire, Jan 1994	250 (hourly)	ED	No change	No change	NA
Phonboon et al. (1999)	Thailand (region-wide)	1997 Asian Haze Sep-Oct 1997	218 (daily) 69 (monthly)	Outpatient	NA	8% increase (net)	No change
Davidson et al. (2003)	Colorado	Hayman Fire 26days	91 (daily) 372 (hourly)	ED	No change	40% increase (P)	NA
				Urgent Care	22% decrease (P)	No change	NA
				Outpatient	No change	NA	NA
Phonboon et al. (1999)	Thailand (Hatyai)	1997 Asian Haze Sep-Oct 1997	218 (daily) 69 (monthly)	Outpatient	No change	7% increase (net, all respiratory disease)	No change
Duclos et al (1990)	CA, USA	Aug-Sep 1987 (16)	237 (daily)	ED	40% increase (P)	50% increase (P)	NA
Ovadnevaitet al. (2006)	Lithuania	Aug-Sep 2002 (18 days)	275 (daily)	Health center visit	Increased by 1.5-20.5 fold (T)	Increased by 1.5-19.6 fold (T)	NA
Viswanathan et al. (2006)	CA, USA	Oct-Nov 2003	294 (daily)	ED (chief complain)	Increased by 5% (P)	Increased by 4-5% (P)	No change

Mott (2002)	CA, USA	Aug-Sep 1997	Exceed 500 (daily)	Medical center visit	NA	Increased by 52% (T), increased by 9-20% (P)	NA

By time-series method

Study	Location	Name and studied date of wildfire	Max PM10 level	Patient type	Effect on Asthma	Effect on Respiratory system*	Effect on Cardiovascular system
Smith et al. (1996)	Sydney, Australia	Jan 1994 (2 weeks)	250 (hourly)	ED	No change	No change	NA
Johnston et al. (2002)	Darwin, Australia	Long bushfire between April 1st – October 31st 2000	70 (daily)	ED	*Linear model*: 18% increase with 10ug/m3 increase of PM10 *Categorical model*: From base (<10ug/m3) to high (>40ug/m3) PM10 level is associated with 92%-256% increase of admission (depends on lag).	NA	NA
Chew et al. (1995)	Singapore	1994 forest fire in Indonesia	More than 158 (daily)	ED, children	Significant increase	NA	NA
Phonboon et al. (1999)	Thailand (region-wide)	1997 Asian Haze Sep-Oct 1997	218 (daily) 69 (monthly)	Outpatient	1ug/m3 increase of monthly average PM10 is associated with 13 excess admission	Not significant	NA
	Thailand (Hatyai)	1997 Asian Haze Sep-Oct 1997	218 (daily) 69 (monthly)	Outpatient	NA	1ug/m3 increase of daily average PM10 is associated with 0.2 excess visits	NA
Shahwahid and Othman (1999)	Malaysia	1997 Asian Haze Aug-Oct 1997	API=831 (extremely high)	Outpatient	NA	1 unit of increased API measure is associated with 0.0125 case per 10,000 people**	

*: include general respiratory symptom, upper respiratory infection, or obstructive respiratory disease
**: The original classification of disease is "cardiorespiratory illness"
(P): proportion of the number of patient
(T): Total number of patient
NA: Etimates not available

Table 6: Per unit economic value used in U.S.EPA (1999)

	U.S.EPA value (US$ 2007)	Source, description
Mortality	$7.6 million	Pooled estimate from 26 VSL studies (21 from hedonic wage model, 5 from contingent valuation method). (WTP)
Hospital Admission		
All respiratory	$10,971	Elixhauser (1993): Medical cost and labor loss during hospitalization. (COI)
All cardiovascular	$15,105	
ED visits	$308	Asthma only, Smith et al. (1997). (COI)
Respiratory illness and symptoms		
Acute Bronchitis	$71	Neumann et al. (1994)
Asthma attack or moderate or worse asthma day	$50	Row and Chestnut (1986) (WTP)
Acute respiratory Symptoms	$28	Based on the mid-range estimate of WTP by Industrial Economics Incorporated.
Upper respiratory Symptoms	$30	Based on the mid-range estimate of WTP by Industrial Economics Incorporated.
Lower respiratory Symptoms	$19	Based on the mid-range estimate of WTP by Industrial Economics Incorporated.
Shortness of breath, chest tightness or wheeze	$8	Mean of the median estimates from Dickie and Gerking (1991) and Loehman et al. (1979).
Work days loss	$131	Median weekly wage (for 5 days) (COI)
Mild restricted activity days	$60	Tolley et al. (1986) (WTP)

Source: created from Table H-3, U.S. EPA (1999) p.H-21 - H-26.

Table 7: Summary of previous WTP estimation of cardiorespiratory morbidity damage

	Type of sample (n)	Degree of severity	Day(s) or frequency	WTP estimate Mean/median (US$ 2007)
Acute Illness (general)				
Dickie and Messman (2004)	Adult (284)		1	n.a./90
		Mild	1	n.a./81
		Severe	1	n.a./137
	Children (284)		1	n.a./193
		Mild	1	n.a./154
		Severe	1	n.a./262
	Adult (284)		24	n.a./209
		Mild	24	n.a./151
		Severe	24	n.a./256
	Children (284)		24	n.a./444
		Mild	24	n.a./287
		Severe	24	n.a./488
Acute bronchitis				
Navrud (2001) (study in Norway)	Adults (430)		1	29/10
	Adults (493)		14	82/29
Shortness of breath				
Dickie and Messman (2004)	Adult (284)		6	n.a./129
	Adult: have had symptoms		6	n.a./131
	Adult: have not had symptoms		6	n.a./125
	Children (284)		6	n.a./246
	Children: have had symptom		6	n.a./255
	Children: have not had symptom		6	n.a./244
Navrud (2001) (study in Norway)	Adults (433)		1	38/14
	Adults (493)		14	119 /43
Loehman et al. (1979)	Adults (404)	Mild	1	n.a./9
	Adults (400)	Severe	1	n.a./31
		Mild	7	n.a./39
		Severe	7	n.a./103
		Mild	90	n.a./103
		Severe	90	n.a./280.68
Dickie et al (1987)	Adults (8)	Out of breath easily	1	1.14/0
Coughing/sneezing				

Dickie and Messman (2004)	Adult (284)		6	n.a./143
	Adult: have had symptoms		6	n.a./134
	Adult: have not had symptoms		6	n.a./152
	Children (284)		6	n.a./273
	Children: have had symptom		6	n.a./260
	Children: have not had symptom		6	n.a./296
Navrud (2001) (study in Norway)	Children (188)		1	14/2
	Adults (493)		14	38/14
			1	31/8
	Children (206)		14	109/43
	All other household member (424)		1	98/36
	All other household member (474)		14	270/102
Dickie et al. (1987)	Adults (25)		1	2/0
Tolley et al. (1994)	Adults (199)		1	47/ n.a.
			30	316/n.a.
Loehman et al. (1979)	Adults (404)	Mild	1	n.a./6
		Severe	1	n.a./19
		Minor	7	n.a./22
		Severe	7	n.a./57
		Minor	90	n.a./65
		Severe	90	n.a./145
Chest pain/tightness/Agina episode				
Dickie and Messman (2004)	Adult (284)	Chest pain	6	n.a./101
	Adult: have had symptoms		6	n.a./85
	Adult: have not had symptoms		6	n.a./106
	Children (284)		6	n.a./193
	Children: have had symptom		6	n.a./166
	Children: have not had symptom		6	n.a./208
Chestnut et al. (1996)	Adults (16)	Angina episode	1	45/ n.a. (based on averting behavior method)
	Adults (22): exclude very high response		4/month	385/ 190

	Adults (20): exclude very high response		8/month	414/190
Dickie et al. (1987)	Adults (11)	Chest tightness	1	9/2
Head congestion				
Loehman et al. (1979)	Adults (404)	Minor	1	n.a./11
		Severe	1	n.a./23
		Minor	7	n.a./27
		Severe	7	n.a./58
		Minor	90	n.a./72
		Severe	90	n.a./177
Headache				
Navrud (2001) (study in Norway)	Adults (435)		1	25/7
	Adults (491)		14	111/29
Tolley et al. (1994)	Adults (199)		1	76/ n.a.
	Adult (284)		30	927/ n.a.
Dickie et al. (1987)	Adults (16)		1	8/4
Multiple symptoms (cough, shortness of breath, chest pain, fever)				
Dickie and Messman (2004)	adults		6	n.a./202
	children		6	n.a./384
Multiple symptoms (cough, sinus congestion, throat congestion				
Navrud (2001) (study in Norway)	Adults (453)		1	53/21
	Adults (512)		14	162/72
Tolley et al. (1994)	Adults (199)		1	124/ n.a.
			30	1187/ n.a.
Asthma day				
Navrud (2001) (study in Norway)	Adults, asthmatic (25)		1	236/39
	Adults, asthmatic (30)		14	361/101
	Adults, non-asthmatic (418)		1	114/39
	Adults, non-asthmatic (459)		14	343/ 122
	Children: asthmatic (13)		1	502/203
	Children: asthmatic (13)		14	1004 /327
Row and Chestnut (1986)	Asthmatics	Mild	1	45/ n.a.
		Moderate	1	89/ n.a.
		Severe	1	133/n.a.
		Very severe	1	175/ n.a.
		Mild	5	112/ n.a.
		Moderate	5	221/ n.a.
		Severe	5	330/ n.a.

		Very severe	5	436/ n.a.
		Mild	15	211/ n.a.
		Moderate	15	413/ n.a.
		Severe	15	614/ n.a.
		Very severe	15	813/ n.a.
		Mild	50	415/ n.a.
		Moderate	50	817/ n.a.
		Severe	50	1212/ n.a.
		Very severe	50	1603/ n.a.
Sinus congestion				
Navrud (2001) (study in Norway)	Adults (432)		1	28/10
	Adults (485)		14	80/29
Tolley et al. (1994)	Adults (199)	Sinus pain	1	66/ n.a.
			30	504/n.a.
Dickie et al. (1987)	Adults (20)		1	3/2
Throat congestion				
Navrud (2001)	Adults (434)		1	14/ 3
(Study in Norway)	Adults (492)		14	36/14
Tolley et al. (1994)	Adults (199)		1	55/ n.a.
			30	391/n.a.
Eye itching				
Navrud (2001) (study in Norway)	Adults (433)		1	19/ 7
	Adults (489)		14	63/21
Tolley et al. (1994)	Adults (199)		1	52.68/ n.a.
			30	447/ n.a.
Could not breathe deep				
Dickie et al. (1987)	Adults (17)		1	5/ 0
Pain on deep breath				
Dickie et al. (1987)	Adults (8)		1	11/4
Wheezing/whistling breath				
Dickie et al. (1987)	Adults (6)		1	5/0

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